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New high S/N observations of the ^{6}Li/^{7}Li blend in HD 84937 and two other metal-poor stars*

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Abstract. High signal to noise ratio spectra have been obtained with the GECKO spectrograph at CFHT, at a spectral resolution of 100 000, for three metal-poor stars in order to obtain more accurate abundances of the very fragile element ^{6}Li. For two newly observed stars, BD +42 2667 and BD +36 2165 it appears that the first may have a detectable amount of ^{6}Li, whereas no ^{6}Li is found in the second one. The S/N ratio of only a few hundreds obtained for these two faint stars preclude however a firm conclusion. For the third star, the well known object HD84937, a very high S/N of 650 per pixel (over 1000 per resolved spectral element) was obtained, yielding greatly improved accuracy over previous determinations. A value of ^{6}Li / ^{7}Li = 0.052 ± 0.019 (one sigma) is obtained. We also conclude that the no- ^{6}Li assumption is ruled out at the 95 per cent level, even in the most permissive case, when a variation of all the other free parameters (wavelength zero-point, continuum location, macroturbulent broadening, abundance of ^{7}Li) is allowed.

The possibility that the ^{6}Li feature is an artifact due to a once suspected binarity of HD 84937 is discussed, with the conclusion that this assumption is ruled out by the extant data on the radial velocity of the object. The ^{6}Li abundance is compared with recent models of formation of the light elements Li, Be and B. This comparison shows that ^{6}Li is either undepleted, or only moderately depleted in HD 84937, from its initial value. Under the assumption that the atmospheric depletion of ^{6}Li and ^{7}Li in stars is by slow mixing with hot layers (underneath the convective zone), in which these elements can burn, we conclude that the depletion of ^{7}Li by this mechanism in HD 84937 is less than 0.1 dex.

This new upper limit to the efficiency of the depletion of ^{7}Li by slow mixing burning, in a star located on the Spite plateau, leads to a more secure estimation of the primordial abundance of ^{7}Li. However, the effect of temperature inhomogeneities in the convective zone, on the derived abundance of lithium still remains to be accurately determined.

Key words: stars: abundances – stars: individual: BD +362165 – stars: individual: BD +422667 – stars: individual: HD 84937 – stars: Population II – cosmology: observations

1. Introduction

The ^{6}Li isotope is an element of considerable interest, but extremely difficult to observe, as a weak component of a blend involving the much stronger doublet of ^{7}Li, and with an isotopic separation of only 0.16 Å. So far, it has been unambiguously detected in only two stars, HD 84937 (Smith et al. 1993, Hobbs & Thorburn (1994), and HD 338529 = BD +26 3578 (Smith 1996; Smith et al. 1998). It has been unsuccessfully searched in five other halo stars by Hobbs & Thorburn (1997) and in 8 more by Smith et al. (1998). We have decided to reobserve HD84937 (for which the 1 σ error bar on the abundance is one-half of the abundance found; the best case!) with a signal/noise higher than obtained so far, and two other metal-poor stars in which we hoped to have a new detection of ^{6}Li.

Let us recall the double interest of obtaining evidence for ^{6}Li, in halo stars. ^{6}Li is a rare and fragile isotope of spallative origin, as are ^{9}Be, ^{10}B and ^{11}B. It is destroyed in stellar interiors at a temperature of about 2×10^6 K, lower than the temperature of 2.5×10^6 K at which ^{7}Li is also destroyed.

The first interest of finding ^{6}Li in a halo star lying on the ^{7}Li Spite plateau, is the strong presumption that, if ^{6}Li has survived, it is unlikely that the less fragile element ^{7}Li has been significantly depleted in the star. The ^{7}Li abundance on the Spite plateau can then be taken as representing the cosmological abundance of ^{7}Li, predicted by the standard Big Bang nucleosynthesis (Schramm & Turner 1998).

The second interest is to compare the ^{6}Li abundance observed, with the predictions of recent theoretical models of spallation (Duncan et al. 1992, Vangioni-Flam et al. 1994, 1996, 1997). These models have been triggered by the discovery that the other spallative nuclei Be and B have an abundance increasing linearly with metallicity in metal-poor stars (Boesgaard and King 1993, Boesgaard 1996, Duncan et al. 1997, Molaro et al. 1997). More specifically, Vangioni-Flam et al. (1997) have pre-

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dicted the production ratios of ^{6}Li, ^{7}Li, Be, ^{9}B, ^{11}B by low-energy accelerated nuclei from SNe II, impinging the overwhelmingly dominant species in the early interstellar matter: H, and ^{4}He. Recently Lemoine et al. (1997) have dicussed extensively the abundance found earlier for ^{6}Li in the light of these recent predictions. Let us recall that the dominant processus of formation for ^{6}Li is the $\alpha + \alpha$ reaction, now believed to occur between α particles accelerated in SNe II ejecta colliding with α particles of the surrounding interstellar matter (ISM). This sets the initial abundance of ^{6}Li in the star formed from this ISM, and part of this ^{6}Li may be subsequently burnt in the star, where we observe the remaining fraction. The initial ^{6}Li can be inferred from the predicted ^{6}Li /Be ratio, and the observed Be abundance (see also Molaro et al. 1997). The depletion of ^{6}Li within the star, by the ^{6}Li(p,^{3}He)^{4}He process, is obtained by comparing the observed abundance of ^{6}Li in the star to the estimated initial abundance. Models of lithium burning by mixing of the convective zone with deeper layers allow to translate the estimated depletion level of ^{6}Li into some maximum depletion level for ^{7}Li in the same star (Cayrel et al. 1999).

For this approach it is of course vital to be sure that ^{6}Li is present. It is why we have decided to observe HD 84937 with a higher S/N ratio, and to observe two other halo stars, not yet analyzed for ^{6}Li, BD +42 2667 and BD +36 2165. Actually BD +42 2667 was also analyzed in parallel by Smith et al. (1998), but we were not aware of the work at the time of our observations. The observations and the method of data reduction are described in Sect. 2. Sect. 3 is the analysis of the data in terms of ^{7}Li and ^{6}Li respective abundances. Sect. 4 is devoted to the case of HD 84937. Sect. 5 gives the results for the two other stars. Sect. 6 discusses the significance of our results, and Sect. 7 summarizes our conclusions.

2. Observations and data reduction

Spectra of the three selected stars HD 84937, BD +42 2667 and BD +36 2165 were obtained with the spectrograph GECKO at the 3.6m CFHT telescope in Hawaii (the log-book of the observations is given in Table 1). The resolving power of the spectrograph, measured on thorium lines, is $R = 100000$. The spectra were centered at 6710 Å, the region of the Li I resonance doublet. In order to check the width of the lines, a spectrum of HD 84937 was also obtained in the region of the stronger, well defined, calcium line at $\lambda = 6162$ Å. The detector was a 2048x2048 15 μm pixels CCD fabricated by Loral. The nominal gain of this CCD is 2.3 e ADU^{-1}, the read out noise 5.3 e pixel^{-1}, totally negligible on our well exposed spectra. The pixel width was $15\ \mu$m, corresponding to 0.02698 Å.

All the spectra have been reduced with a semi-automatic code specially developed at Observatoire de Paris-Meudon (Spite 1990). It performs the optimal extraction of the spectrum, the flat fielding and the wavelength calibration from the comparison lamp spectrum. The wavelength calibration was performed with a argon-thorium lamp. The laboratory wevelengths were taken in Palmer & Engelman (1983) for thorium, and in Kaufmann & Edlen (1974) for Argon. The rms of a third order polynomial fit, corrected for the actual number of freedom, is of the order of 0.003 Å. It must be noted that, as it is well known (and e.g. it is alluded to by Hobbs & Thorburn 1997), the collimation angle between the beam of the lamp and the stellar beam, makes that there is a possible zero point shift between the wave length scale of the stellar and lamp spectra, and this shift may change during the night. Moreover, as the exposure time for the thorium lamp is about one hour, the calibration spectra were usually taken at the beginning and at the end of the night. The thorium spectra are quite usable for establishing a calibration curve, but their zero-point can be slightly shifted at the time of the stellar exposure. This is why we have determined the zero-point of the wavelength scale mostly from the position of the calcium $\lambda = 6717$ Å line, taken in the same exposure as the lithium feature. Although the calcium $\lambda = 6162.172$ Å line (wavelength from Sugar & Corliss 1982) is better defined, it was not used for wawelength zero-point determination, for the reason explained above.

Table 1. Log book of the observations

HD/BD mag.	date of obs.	UT beg.	exp. time mn	central wavele. Å	estim. S/N
84937	970420	6h10	120	6712	390
V=8.28	970420	8h20	90	6712	300
	970421	5h30	120	6162	380
	970421	8h10	120	6712	350
+42 2667	970420	11h30	240	6712	240
V=9.86	970421	10h50	250	6712	230
	970422	10h30	270	6711	280
+36 2165	970422	5h45	240	6711	280
V=9.78					

Flat-fielding has been done using a quartz lamp and a rapidly rotating hot star. Due to small fringes produced by the CCD in the spectral range of the lithium line, the hot star has been finally preferred for flat fielding.

The stellar broadening (≈.15 Å is clearly larger than the spectrograph resolution (≈ 0.07 Å), and thus the stellar profiles are dominated by intrinsic stellar broadening.

3. Analysis

The models used in the analysis of the stars have been interpolated in the grid defined by Edvardsson et al. (1993) computed with an updated version of the MARCS code of Gustafsson et al. (1975) with improved UV line blanketing (see also Edvardsson et al. 1994). The physical parameters of the models have been taken from the literature and are given in Table 2.

The effective temperatures are all consistent with the Alonso et al. (1996) scale, based on the Infrared Flux Method (Blackwell & Shallis 1977). The microturbulence has been set to 1.5 km sec^{-1}, following Smith et al. (1993). The ^{6}Li /^{7}Li ratio is not sensitive to the exact temperature adopted, only the absolute values are affected by the uncertainty on the zero point of

Table 2. Main parameters of the adopted model atmospheres

star HD/BD	Teff K	log g (CGS)	[Fe/H] dex	Ref
HD 84937	6300	4.0	−2.3	Nissen et al. (1994)
+42 2667	6059	4.0	−1.7	Rebolo et al. (1988)
+36 2165	6350	4.8	−1.2	Axer et al. (1994)

the effective temperature scale. To estimate the ^{6}Li / ^{7}Li ratio, we have proceeded very much as done in the seminal paper by Smith et al. (1993). Having used the same atomic data for the lithium feature, we have considered as adjustable parameters, in the fitting of a synthetic spectrum to an observed spectrum, the five parameters (i) placement of the continuum, (ii) and (iii) abundances of the two elements ^{6}Li and ^{7}Li, (iv) macroscopic broadening of the lines (encompassing instrumental profile, star rotation and macroscopic motions in the atmosphere of the object), and (v) wavelength zero-point adjustment. The profile of the macroscopic broadening was assumed to be gaussian and is defined by its full width at half maximum FWHM. The permissible range of this last parameter was determined by the observation of the two calcium lines at 6162 and 6717 Å.

Each time, the quality of the fit between 27 points of the synthetic versus observed data points was computed and shown graphically. The quality of the fit has been quantified by its χ^2, The parameters have been determined by the Maximum-Likelihood approach, i.e. by trying to minimize the χ^2, in the permissible range of variation of the parameters.

In order to compute the χ^2, one must know the value of the observational standard error on each of the data point. When several spectra were available we have co-added them. As we had a spectral resolution higher than needed to separate the isotopic shift of 0.16 Å between the ^{6}Li and ^{7}Li lines, we have also convolved the coadded spectra by a gaussian of FWHM = 1.66 pixel ≈ 0.045 Å. Before this convolution the S/N on each data point was 650 for HD 84937 (estimated in segments of the continuum, and consistent with the expected photon noise). After convolution it raised to 1020 (noise filtering). This represents a significant improvement in S/N, without a damaging loss of resolution. One must realize however, that the classical χ^2 test is not directly applicable to the filtered spectrum, because the filtering introduces a correlation between data point values. So we have computed (see appendix) the applicable pseudo-χ^2 probability function for the quantity X^2:

$$X^2 = \sum_{i=1}^{n} (\frac{O_i - C_i}{\sigma_i})^2$$

where the O_i have been smothed by the convolution performed. Following a widely used notation, the C_i are the computed values of the synthetic spectrum, and σ_i is the noise on the i_{th} data point. As it will be explained in detail further, this approach permits a more powerful discrimination of the weak signal produced by the ^{6}Li feature, thanks to the improvement in the S/N ratio.

Because of its particular interest we discuss in the following section, in more detail, the case of HD 84937.

4. HD 84937

4.1. Fitting the observations with a synthetic spectrum

It is often considered (Smith et al. 1993) that there are chiefly two methods for determining the isotopic ratio ^{6}Li / ^{7}Li. The presence of ^{6}Li modifies the blend in (i) modifying the center of gravity in wavelength of the feature and (ii) modifying the line profile by increasing the opacity on the red wing. The first one is referred to as the "c.o.g" method, and the second as "line profile analysis". However both effects are combined in the spectrum synthesis approach. Smith et al. (1993) have pointed out that the "c.o.g." method is vulnerable to a possible differential convective blue shift between the formation of the Li blend and the only available other line in the spectral field, the Ca I 6717.687 (Pierce and Breckinridge 1973).

Actually, the blue shifts of solar lines have a fairly large range of values (from $-0.7\,\mathrm{km\,s^{-1}}$ to zero, see Allende Prieto & García López 1998). Kurucz (1995) has claimed that the effect of convective temperature inhomogeneities could be considerably larger in metal-poor stars than in solar type stars. Bonifacio & Molaro (1998) have given a strong counter-argument concerning the claim of a large effect on the abundance of Li, but the question of a wavelength shift remains. Furthermore, Smith et al. (1998) (this work came to our knowledge after we wrote the submitted version of this paper) cite an unpublished work by Rosberg and Johansson giving a λ of 6717.677 for the line instead of 6717.687 we first used. They also mention that if the c.o.g method gives a slight shift in the right direction for HD 84937 it gives a blue shift, in contradiction with the result of the line profile analysis, for the other star, BD +26 3578. Quantitatively speaking, the c.o.g. method is clearly far inferior to the line profile analysis, a differential blue shift of only 0.001 Å corresponding to a relative change of 20 per cent in the ^{6}Li/ ^{7}Li ratio (Smith et al. 1998), whereas such a shift has no influence on the line profile analysis, as being negligible with respect to the isotopic shift of 0.16 Å. Martin Asplund (private communication) has investigated from hydrodynamical simulations of convection, the size of differential blue shifts between the lithium feature and Ca I, 6162 and 6717. His preliminary results are that the Ca I lines are blue-shifted with respect to the lithium feature in HD 84937, by 0.2 to $0.4\,\mathrm{km\,s^{-1}}$. This is enough to completely kill the c.o.g. method, the corresponding variation in wavelength being 9 mÅ, larger than the shift between 5 per cent of ^{6}Li and no ^{6}Li at all. Therefore, the safest approach, adopted here, is to consider that all relevant parameters are allowed to vary, including the zero-point of the wavelength scale, and then comparing this least-square solution to the values of the parameter which can be externally determined from other lines, *but allowing for the error bars on these external determinations*. This is what Smith et al. (1993) and Hobbs and Thorburn (1997) have also done, concluding that the constraints on the ^{6}Li/^{7}Li ratio was significantly relaxed by this approach, a price to pay for not being dependent on assumptions on convective shifts, or

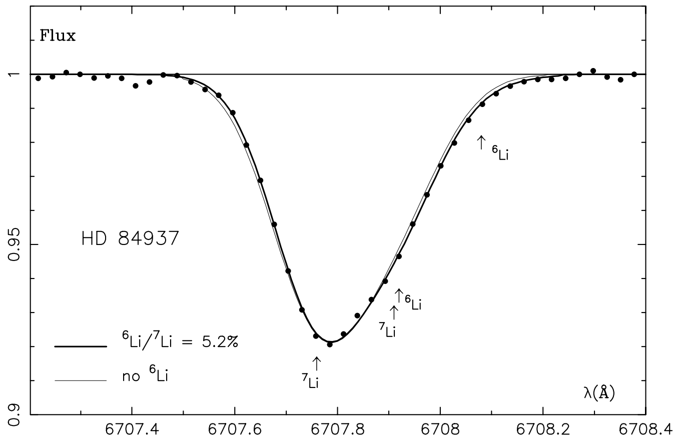

Fig. 1. Observed and synthetic profiles of the blend ^{6}Li,^{7}Li for HD 84937. The synthetic profile has been computed using the stellar parameters given in Table 2. Here the five parameters (abundances of the two lithium isotopes, location of the continuum, zero-point adjustment of wavelength scale, FWHM of the convolution taking care of the broadening of the lines by macroscopic motions and instrumental resolution), have been simulteanously least-square adjusted. The dots are the observations. The thick line represents the best fit obtained [log(^{7}Li /H)=2.212, log(^{6}Li /H)= 0.928, FWHM= 0.148 Å, wavelength shift = 10 mÅ, continuum redadjustment −0.0006]. The thin line represents the (degraded) fit when the ^{6}Li abundance is forced to zero, without further readjustment of the zero-point of the wave-length scale, but all the other parameters being readjusted: ^{6}Li /H=0.0, log(^{7}Li /H) = 2.235, FWHM= 0.163 Å].

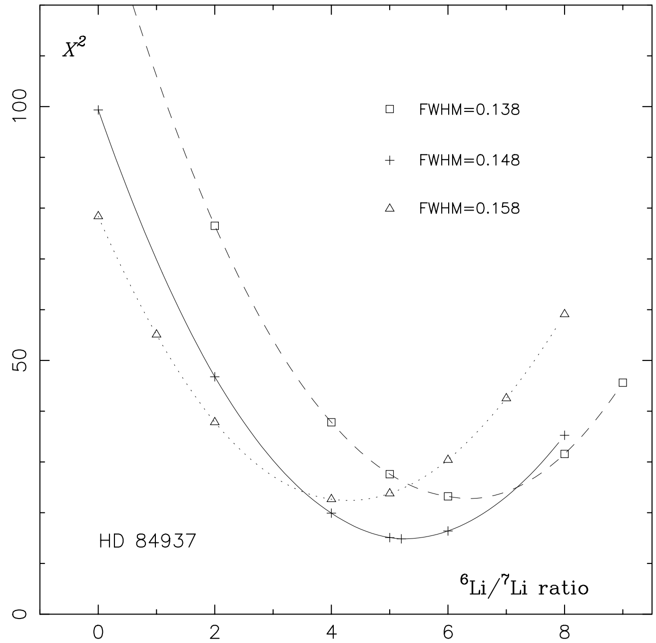

Fig. 2. Fine tuning for the determination of the macroscopic broadening of the lithium feature. A broadening of FWHM ≈ 0.15 gives the smallest residuals, and this for a ^{6}Li / ^{7}Li ratio of 5.2 per cent.

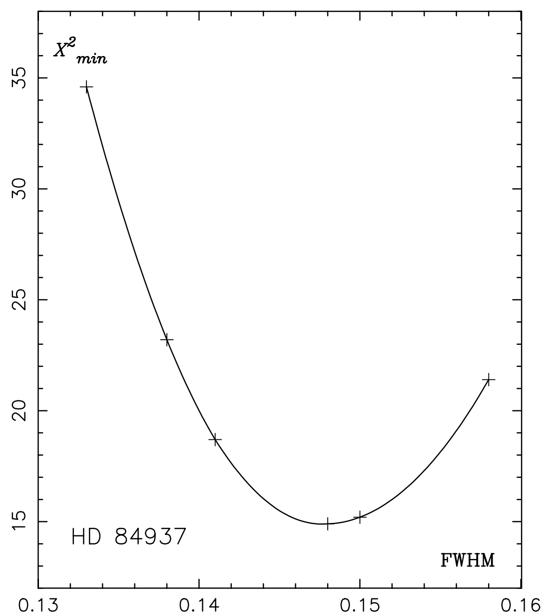

Fig. 3. Interpolation, based on the results shown in Fig. 2, for finding the optimal value of the FWHM of the macroscopic broadening. The value at the minimum minimorum is 0.148 Å.

ignoring that the macro-broadening of the lines cannot be fixed exactly.

The situation is illustrated by the Figs. 1 to 4. First we consider as free parameters the position of the continuum, the abundance of the two isotopes of lithium, the macroscopic broadening (due to stellar rotation, macroscopic motions in the stellar atmosphere, and finite resolution of the spectrograph) and the poorly determined zero-point of the wavelength scale. The best fit to the data point, allowing the 5 parameters to vary, is shown by the full line of Fig. 1. This best fit is obtained for the following values: ^{6}Li / ^{7}Li = 5.2%, log(^{7}Li/H)=2.088, FWHM= 0.148 Å, and an adjustment of the ordinate scale of 0.06 per cent and of the zero point in wavelength by 10 mÅ. The residuals of this fit are shown in Fig. 4. The rms of the fit on 27 points with the unfiltered data is 0.00120. The expected value of the χ^2 for 27 points and 5 adjusted parameters is 22 for a perfect model, and the value found for the fit is 16.4. With the filtered data the corresponding numbers are rms = 0.00073, 22 and 15. This means that the model represents the data without the need of increasing the number of the parameters, and that the realization of the noise corresponding to our observation is slightly better than its mathematical expectation, but reasonably close to it. Now we can compare the value of the zero-point wavelength shift and the value found for FWHM with the accuracy of our wavelength scale and the value of FWHM determined from the Ca I lines. The expected accuracy of our wavelength scale is dominated by the uncertainty on the exact wawelength of the 6717 line, plus the unknown value of the differential blue-shift between the Li lines and the 6717 Ca I line. This is of the order of 0.6 km s^{-1}, or 13 mÅ. The shift obtained for the Li I feature *with the new value 6717.677 for the laboratory value of the Ca I line* is −10 mÅ. This is within the uncertainties, although not in the direction predicted by Asplund. However, the Ca I line is strongly blended in the Sun, and very weak in HD 84937, so any conclusion based on such a small shift would be a clear

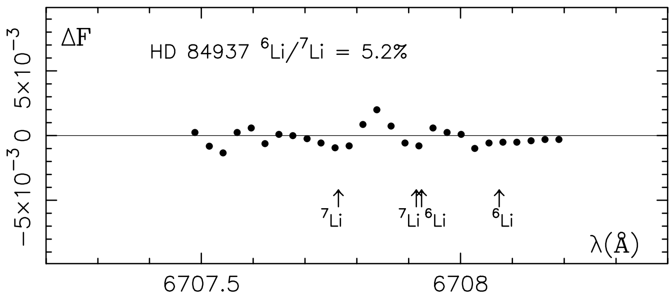

Fig. 4. Residuals (O-C) of the best fit obtained with 5.2 per cent of ^{6}Li. The rms of the fit between the synthetic spectrum and the filtered observed spectrum is 0.73E-03. The expected rms for a perfect synthetic model and the noise level computed from photon noise is 0.98E-03, so the fit is slightly below the expectation value, for a perfect model, quite possible for a particular realization of a random noise.

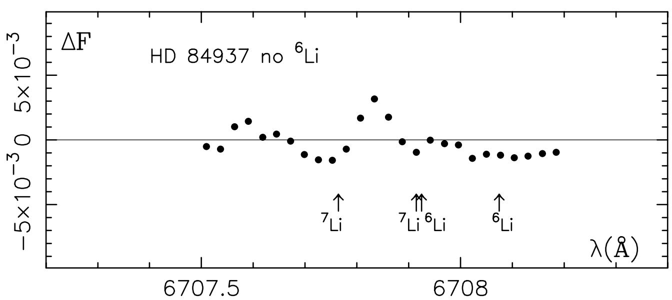

Fig. 5. This figure show the residuals of the best fit, when the abundance of ^{6}Li is forced to zero, all the four other parameters being allowed to vary. This best fit for no ^{6}Li has now a rms of 1.19E-03, significantly larger than the rms of the best fit with 5.2% of ^{6}Li (0.73E-03). The X^2 of this fit is 39.8, excluding the model at a level of confidence of 95.3 per cent.

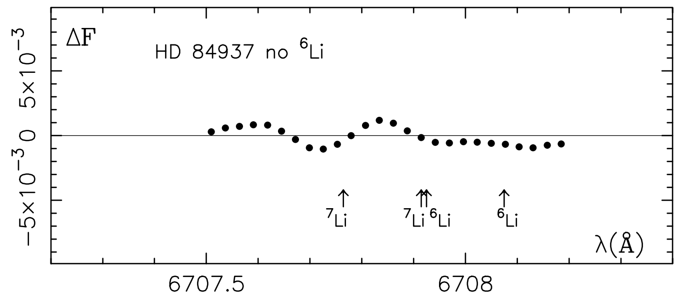

Fig. 6. Residual of the synthetic spectrum corresponding to the best fit with no ^{6}Li, and a wavelength offset of 0.005 Å, relative to the synthetic spectrum corresponding to the best fit with 5.2% of ^{6}Li and no wavelength shift. These residuals are not produced by noise, but by the intrinsic difference between the two spectra. The necessity of working at a very high S/N ratio is demonstrated by this comparison, the amplitude of this differential signal being of the order of a couple of thousandths only. *Note* the striking similarity with Fig. 5, giving the feeling that the shape of the residuals of the fit with no ^{6}Li shows the signature of a wrong choice of the parameters.

overinterpretation of the data. The external values of FWHM are respectively 0.150 Å± 0.01 (6717 line) and 0.153 ± 0.08 (6162 line, slightly saturated). The best fit (0.148 Å) is totally compatible with the external values, which, unfortunately, do not allow to restrict efficiently the internal uncertainties.

Now we retry the fit, forcing the abundance of ^{6}Li to zero, but keeping the 4 other parameters free. We get a different solution, with log(^{7}Li/H) = 2.233, FWHM= 0.158, a differential redshift with Ca I 6717.677 of 0.005 Å and a negligible change in the continuum position. The residuals of this new fit are shown in Fig. 5. The rms of the fit is 0.00119 (with the continuum at 1.0), corresponding to a value of X^2 of 39.8, rejecting this no-^{6}Li model with a confidence level of 95.3 per cent. Would we have used the unfiltered spectrum, the rms of the fit would have been 0.00155, corresponding to a χ^2 of 27.3 for an expectation value of 27-4=23, which is excluded only at the 76 per cent level. However, many authors use a reduced relative χ^2/ν, not bothering for estimating the noise independently. In that case the unfiltered χ^2 being 16.4 for the best fit with 5.2 per cent of ^{6}Li, one can claim that the χ^2 has been degraded in the ratio 27.3/16.4 when the expected degradation is 24/23. The probability of such a difference is only about 3 per cent. Of course the same approach can be also applied to the filtered data, leading to an exclusion of the zero ^{6}Li hyphothesis at the 99.5 per cent level. We do not support these numbers, too optimistic, and we suggest instead to bring, now more attention to the run of the residuals with wavelength.

The shape of the residuals with wavelength is very suggestive of being not due to a random noise. In order to check if this is the case we have compared two synthetic spectra (*no noise here*), one corresponding to the absolute best fit, the other one corresponding to the best fit, with no ^{6}Li, involving a 0.005 Å shift in wavelength. The residuals of the second versus the first one are shown in Fig. 6. The similarity between Figs. 5 and 6 is striking. Fig. 6 also shows how important it is to reach a S/N of 1000, to discriminate between these two cases. We consider that the rejection of a zero-abundance of ^{6}Li at the 95 per cent level, *in the most permissive case*, represents a serious advance with respect to former works, done with a lesser S/N ratio.

A Bayesian approach of the problem, that we have not attempted, is likely to increase our value of ^{6}Li, because of the *a priori* positive physical nature of the abundance of ^{6}Li. For shifts larger than 0.005 Å the solution would need ^{6}Li in emission, not acceptable. The 68 per cent probability around the optimal fit (^{6}Li /^{7}Li = 0.052) can be computed when the continuum level, and the two abundances are free parameters, because they occur linearly. We find that this amounts to $\pm$ 0.012. An extra-allowance must be made for the impact of the uncertainties on the other two parameters. For the FWHM of the broadening, if we accept the full range of Fig. 2, with equal probability of the FWHM in the range, we obtain an extra contribution of $\pm$ 0.007. The contribution of a zero-point shift in wavelength is more difficult to estimate. A shift as large as the one needed for the no ^{6}Li hyphothesis is largely rejected. We consider that a shift of $\pm$ 0.002 is allowed. This adds an extra-excursion of rms 0.013. The combined effect is 0.019, adding quadratically. A Monte Carlo simulation would be more correct to evaluate

Table 3. Radial velocities of HD 84937 from 1923

RV	weight	epoch	reference
−22.6	3	1923	ApJ 57, 149
−15.3	undef	1940	PASP 52, 401
−12.9	2	1965	MNRAS 129, 63
−16.4	9	1969	AJ 74, 908
−13.1	8	1972	AJ 77, 590
−16.7	8	1979	IAUS 30, 57
−14.8	10	1988−94	AJ 107, 2240
−14.95	20	19940305	Mayor, unpubl.
−15.17	20	19960415	A&A 338, 151
−14.8	15	this paper	from Ca I 6162 Å

this uncertainty, but what is more important is to have excluded a zero abundance of ^{6}Li at the 95 per cent level.

4.2. Could HD 84937 be a binary star?

In one of their papers on proper motion stars (paper XII), Carney et al. (1994) consider HD 84937 as a suspected spectroscopic binary. We have two recent measurements of this star with the OHP instrument ELODIE. We compare in Table 3 these measurements with those of Carney and earlier.

A rather arbitrary weight (20) has been attributed to the two values obtained with ELODIE which have a standard error of 0.25 km sec^{-1}. There is no indication of a systematic variation over 30 years. Moreover, Mayor (private communication 1998) indicates that the star, observed repeatedly with CORAVEL during more than six thousand days, has no variation of radial velocity at the level of 1 sigma = 1.19 km sec^{-1}. If we imagine that the ^{6}Li component is actually the ^{7}Li component of a companion, the radial velocity difference is 7 km sec^{-1}. In order to produce the 5 per cent strength in the blend, the companion must be a dwarf of absolute magnitude about 6.8 having an effective temperature of 5400 K and a mass of 0.6 $M_\odot$, whereas the primary has a mass of about 0.8 $M_\odot$. Because, K_1 and K_2 are the amplitudes of the radial velocity variation of the two components, we have the two constraints: $K_1 + K_2 \geq 7\,\mathrm{km\,sec}^{-1}$ and:

$$\sin^3 i \leq 1$$

and using the well known relation Allen (1985):

$$(M_1 + M_2)\sin^3 i = 1.035.10^{-7}(1 - e^2)^{3/2}(K_1 + K_2)^3 P$$

the following condition is obtained:

$$P \leq 0.966.10^7 (M_1 + M_2)/(343(1 - e^2)^{3/2})$$

Replacing $(M_1 + M_2)$ by its value and taking a typical value of 0.3 for *e*, we get

$$P \leq 45000\,\mathrm{days}$$

or 124 years. This condition is barely acceptable if there is no sign of variation of the radial velocity in 30 years, which represents one fourth of the maximum period. We therefore consider

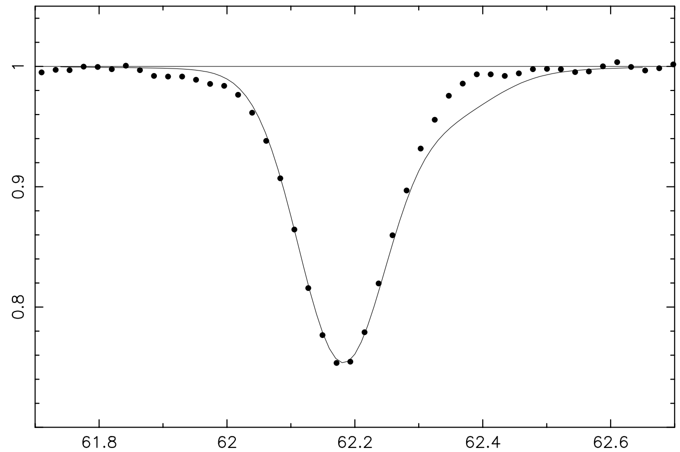

Fig. 7. Comparison between the observed profile of the Ca I line at 6162 Å in HD 84937 and the computed profile if the ^{6}Li feature would be due to a ^{7}Li line of a companion star. The two profiles are clearly not compatible

as rather unlikely the assumption that we see a second ^{7}Li blend instead of a ^{6}Li component. A second implication of the same assumption would be that not only the lithium blend would be affected, but also all other absorption lines. We have computed the effect on the line Ca I 6162, observed in the same run. The computed and observed profiles are strongly discrepant (see Fig. 7).

Again, the binarity explanation of a fake ^{6}Li is discarded. Nevertheless we have asked to two groups to observe HD 84937 in speckle interferometry for checking for a possible companion.

4.3. Why is ^{6}Li found, among very metal-poor stars, only in HD 84937?

It is very embarassing to have a single case of undisputable detection of ^{6}Li out of several very metal-poor stars investigated for the presence of ^{6}Li. What makes HD 84937 so special? We present in Fig. 8, the HR diagram of metal poor stars with distances reliably established by Hipparcos. Clearly, from Hipparcos parallaxes, HD 84937 is among the stars deficient by more than a factor of 100 in metals, also among the evolved subgiants, with BD +26 3578, and HD 140283. It means that it is also one of higher mass, less prone to ^{6}Li burning. HD 140283 is in principle even more favourable from this point of view, but its extremely low metallicity makes it less good for having inherited enough ^{6}Li by spallation, and also the star is possibly evolved enough to have diluted its ^{6}Li in a thick convective zone (Chaboyer 1994). Actually the case the more similar to HD84937 is BD +26 3578, for which ^{6}Li detection has been claimed by Smith (1996) and Smith et al. (1998).

We have theoretically investigated ^{6}Li destruction along the ZAMS in metal-poor stars. The details are described in another paper (Cayrel et al. 1999). The principle on which it is based is that the burning rate has such a fast variation with temperature that ^{6}Li, as well as ^{7}Li, at a given depth below the convective zone, either do not burn in 15 Gyr, or burn so fast that they are

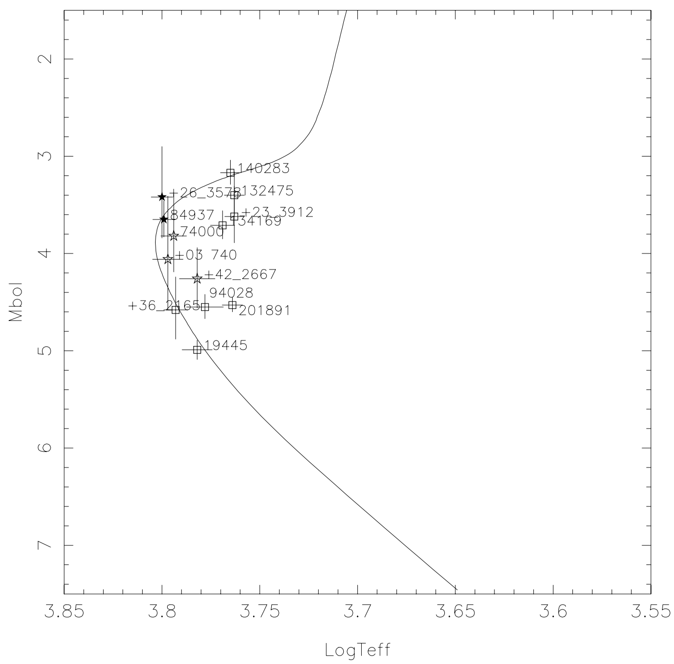

Fig. 8. HR diagram of stars searched for ^{6}Li. The symbols are: a filled star for an unambiguous measurement (only cases HD 84937 and BD +26 3578); an open star for a less solid claimed detection or only an upper limit for ^{6}Li, at a level of 10 to 13 per cent of ^{7}Li. The squares are stars for which ^{6}Li is undetectable, i.e. below 2 per cent of ^{6}Li. The curve is a 14 Gyr VandenBerg isochrone for [Fe/H] = -2, shifted by 0.01 in log(Teff), as needed to fit the high parallax subdwarfs (Cayrel et al. 1997). It is interesting to note that the stars with detected, or possible, ^{6}Li are fairly concentrated near the turnoff, suggesting that ^{6}Li is burned below, and diluted above. All stars have metallicities below [Fe/H] = -1.5, except BD +36 2165 and HD 201891 which are near [Fe/H]= -1. In the name of the stars 'HD' and 'BD' have been omitted.

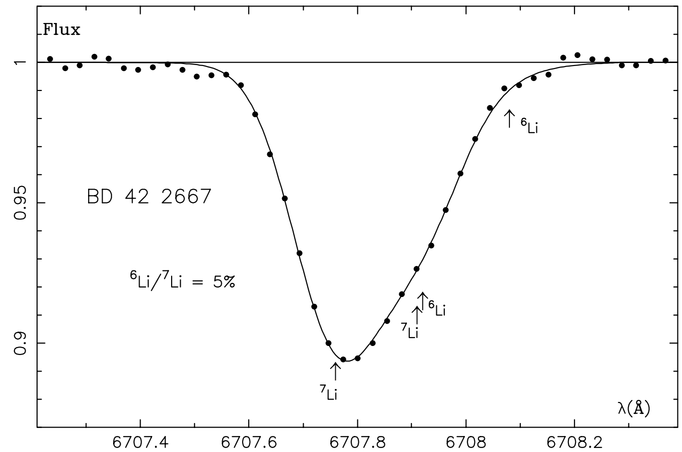

Fig. 9. Best fit of the lithium blend for BD +42 2667. The logarithmic abundances are respectively 2.088 and 0.82 for ^{7}Li and ^{6}Li. A readjustment in wavelength of 5 mÅ was obtained. The FWHM is 0.125 and the rms of the fit 1.59E-03.

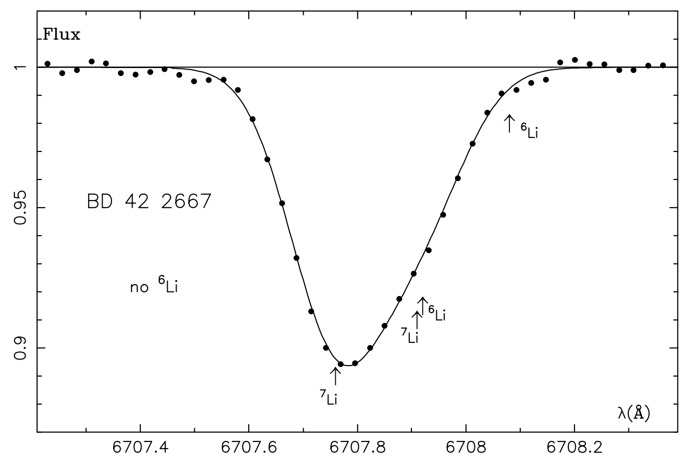

Fig. 10. Fit of the lithium blend for BD +42 2667 with no ^{6}Li. A wavelength shift of 0.008 Å is needed. The logaritmic abundance of ^{7}Li is 2.12. The FWHM is 0.141 and the rms of the fit 1.75E-03.

destroyed in less than 1 Gyr, or so. The rate of decline of the abundance of the element in the convective zone is then controlled by exchange of matter between the convective zone and the deeper zone deprived very soon of the element. This rate is a purely hydrodynamical quantity. So if for example, we find that ^{7}Li is strongly depleted in the convective zone when the burning layer is separated from the convective zone by a layer having a thickness in mass equal to half of the mass of the convective zone, we shall assume that this will hold for ^{6}Li also, taking of course into account the fact that the location of the fast burning zone is moved upwards for ^{6}Li. This allows us to transform the ^{7}Li depletion curve into a ^{6}Li depletion curve. Clearly, at metallicity [Fe/H] = -1.5, only the most massive stars ($M > 0.8 M_\odot$) can save their ^{6}Li. At [Fe/H]c = $-1.$, ^{6}Li even burns *inside* the convective zone, so there is no hope to find any ^{6}Li. We have not yet investigated the dilution effect, above the turn off, but Chaboyer (1994) finds that this process becomes effective at the position of HD 140283. Fig. 8 shows the position of the stars in which ^{6}Li has been found or is possibly present with an abundance less than 10 per cent of the abundance of ^{7}Li. They clearly cluster along the turn off, in agreement with the theoretical expectation. These considerations make understandable that ^{6}Li can be found only in a very limited portion of the HR diagram.

5. The two other stars

Two other stars, BD +42 2667 and BD +36 2165 have been observed. The profile of the lithium line of the first star is best explained by a ^{6}Li / ^{7}Li ratio of 10%. And the hypothesis of no ^{6}Li provides a considerably worse fit. If again a shift in wavelength is allowed, the profile may be explained by a ^{6}Li / ^{7}Li ratio of only 5% (Fig. 9), so that the value of the abundance of ^{6}Li may seem rather uncertain. Assuming the hypothesis of no ^{6}Li, a not too bad fit may be found (Fig. 10),

These observations point towards a detection of ^{6}Li in this star, but the modest S/N ratio reached in the observation of this star precludes a conclusion at a very high confidence level.

Smith et al. (1998) have also studied BD +42 2667 and conclude that it has probably no ^{6}Li. We do not fight this conclusion, the residuals being insufficiently apart in the two cases.

The other observed star, BD +36 2165, does not provide any definite detection of ^{6}Li. The S/N ratio reached is even lower, and does not enable any firm constraint.

6. Discussion

The observation of HD 84937 has essential consequences, first on the depletion of ^{6}Li (and indirectly that of ^{7}Li) in Pop II stars, and on the cosmological status of Li/H observed in old metal-poor stars, and also on ^{6}Li (and Be and B) production. The ^{6}Li isotope is a pure spallation product (see Reeves 1994 for a review). This fragile nucleus is burnt at low temperature (about 2.10^6 K) and cannot be synthesized inside stars. Spallation agents are (i) galactic cosmic rays (GCR), specifically acting in the galactic disk through p, α + He,CNO $\rightarrow$ ^{6}Li,^{7}Li and (ii) in the halo phase ([Fe/H] ≤ -1), low energy α,C and O nuclei ejected and accelerated by supernovae, interacting with H and He in the ISM (Cassé et al. 1995, Ramaty et al. 1996). This low energy component (LEC) is likely to be responsible for the linear relationship between Be, B and [Fe/H] discovered recently (Duncan et al. 1997, Molaro et al. 1997, Thorburn & Hobbs 1996, Primas 1996, García López et al. 1998) as shown by Vangioni-Flam et al. (1994). This linear relationship, specifically in the early Galaxy, is due to the fact that freshly synthesized α, C and O from SNe are accelerated at moderate energy and fragment on the H, He nuclei in the ISM. Thus, the production rate is independent of the ISM metallicity (which means that Be and B are " primary"). The ^{6}Li isotope itself is also produced by primary processes, through the two spallative processes GCR and LEC. Consequently, its slope in the ($\log$(^{6}Li /H), [Fe/H]) plane is unity.

The ^{6}Li abundance observed in the atmosphere of HD 84937 is a lower limit to that of the interstellar medium out of which this star has formed since this isotope can be depleted in stellar atmosphere due to proton capture and dilution with Li free material coming from the interior. The depletion factor is still uncertain in spite of many efforts to evaluate it (Lemoine et al. 1997, Chaboyer 1994, Vauclair & Charbonnel 1995, Deliyannis & Malaney 1995).

If ^{6}Li is detected in the atmosphere of a Pop. II star, like HD 84937, one can infer reasonably that the ^{7}Li abundance is essentially unaffected, since ^{7}Li is destroyed at a higher stellar temperature than ^{6}Li, and in this case the Li/H ratio is close to the primordial one.

In this context, it is important to analyze ^{6}Li data versus ^{7}Li and to follow the early rise of the ^{6}Li/H ratio due to the α, C, O + H,He processes described above, as a function of [Fe/H] (evolutionary curve), since this theoretical ^{6}Li/H value represents at any time (metallicity) the initial abundance in the forming stars. Since ^{6}Li can only be depleted in stars, the observed points are located on this curve (no depletion) or below. Previous calculations (Vangioni-Flam et al. 1997) give the Li/H versus [Fe/H] evolution (see their Fig. 1) where the spallative lithium is shown for LEC and GRC. This last component is weaker than the first. Associated to the calculated ^{6}Li / ^{7}Li (their Table 1) the LEC curve allows to predict the evolution of ^{6}Li/H; at [Fe/H] = -2.3 corresponding to the metallicity of HD 84937, the theoretical ^{6}Li/H is slightly below the observation. This characterizes only a specific model. It is possible to find other scenarios able to reproduce all the LiBeB observational constraints, using metal-poor SN II compositions, well suited to the early Galaxy (Woosley & Weaver 1995). This kind of models meets the requirement of a high He/O source ratio, as pointed out by Smith et al. (1998), to explain the high ^{6}Li /^{9}Be ratio. This indicates that if ^{6}Li is destroyed and/or diluted, it is only slightly. This is a challenge for the stellar evolution theory. It is satisfying to see that in this case, the theoretical description of the ^{6}Li evolution in the early Galaxy is globally consistent with our observations. The occurrence of LEC is strenghthened by this observation. This theoretical model has some latitude depending on the composition and energy spectrum of the beam adopted, as said above. It is possible to find some other source composition able to reproduce the LiBeB observational constraints, including the uncomfortably high ^{6}Li / Be ratio found here in HD 84937 by us, and other authors. A further discussion is postponed to a forthcoming paper (Vangioni-Flam et al. 1998).

A word of caution, however. Our analysis is based on the abundance of ^{6}Li in one star, or two when the ratio ^{6}Li / ^{7}Li of 5 percent in BD +26 3578 (Smith et al. 1998) will be confirmed. More precise Be abundances in the two stars would be useful, as well as a richer sample of stars with measured ^{6}Li.

Even assuming that the estimation of the initial ^{6}Li abundance is in error by a factor of 3, our observation shows that ^{6}Li has been depleted by a factor of 3, at the most. The ratio of ^{7}Li depletion to ^{6}Li depletion is model dependent. The burning of ^{7}Li in the region depleting ^{6}Li by a factor of possibly 3 is close to negligible. If ^{7}Li is depleted, it is in deeper layers, where we are sure that the mixing is slower, but by an amount which is very model dependent. Under the simple model we have considered in Sect. 4.3 the depletion of ^{7}Li cannot be more than 0.1 dex if the depletion of ^{6}Li is below 0.5 dex.

Regarding the cosmological consequences of this Li abundance determination and analysis, it is interesting to note that the ^{7}Li abundance ^{7}Li/H = 1.6 10^{-10} in HD 84937:

(i) is for a star which belongs to the Spite plateau and
(ii) is likely to represent the primordial value, once corrected for the small amount of ^{7}Li produced with the ^{6}Li by the LEC process, since ^{7}Li has not been affected by thermonuclear destructions (our above discussion). By comparing this Li/H value with the outcome of standard BBN calculations (Sarkar 1997, Schramm & Turner 1998) this would lead to $\eta_{10} \simeq 2.0$ to 3.5, (or $\Omega_b \simeq 0.02$ to 0.035 for H_0= 60 km s^{-1}.Mpc^{-1}), $Y_p \simeq 0.237$ to 0.245, $D_p/H \simeq 10^{-4}$ to $5{\times}10^{-5}$. This range on D_p/H is compatible with both the high and low values of D/H measured in cosmological clouds on the line of sight of quasars (Burles & Tytler 1998, Webb et al. 1997).

More ^{6}Li, ^{7}Li observations in the atmospheres of old metal-poor stars could strengthen both the argument of occurrence of the LEC process in the early history of the Galaxy, and the use of ^{7}Li as a cosmological test, since the determination of the Spite plateau seems to reflect the true Big Bang value.

7. Conclusions

The main result of this paper is an analysis, with improved accuracy, of the star HD 84937, leading to a new measurement of of ^{6}Li in HD 84937. With a S/N of about 650 per pixel,(1020 on the filtered spectrum) instead of 400 (Smith et al. 1993) and 350 (Hobbs & Thorburn 1994) reached previously, a null abundance of ^{6}Li is now more convincingly ruled out.

The abundance found for ^{6}Li (5.2 per cent of the abundance of ^{7}Li) turns out to be close the expected value of the initial ^{6}Li in HD 84937, using the evolutionary models developed by Vangioni-Flam et al. (1997).

The process of formation of the LiBeB elements just quoted above is now shown to be consistent also for ^{6}Li, provided that the $\alpha + \alpha$ process is the dominant source of ^{6}Li in the early Galaxy.

The nearly equality between the predicted initial ^{6}Li/H value and the observed value in HD 84937 shows that ^{6}Li cannot have been strongly depleted in this star. ^{7}Li, more robust, is necessarily still less depleted, and its abundance can then be taken as representative of the cosmological primordial lithium.

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Appendix

The convolution of the spectra by a narrow gaussian profile of standard deviation $1/\sqrt{2}$ pixel, bringing an unsignificant degradation in spectral resolution, but increasing the signal/noise ratio by 57 per cent, makes the classical χ^2 test inapplicable, because the noise on consecutive pixels becomes correlated. In order to properly discuss the $(O-C)$ residuals, it is necessary to derive the expected mean value of the sum of the $((O-C)_i/\sigma_i)^2$, and its expected variance, in our specific case, where the independent random variables are the noise on each data point, *before* convolution. The convolved signal Y_i is expressed by a linear form of the unconvolved signal y_i (*i* is the running number of the pixel along the Li feature):

Table A1. Probability function of X^2 for 23 degrees of freedom expectation value: 23, variance = 78.2. The second column gives the probability to be in the bin ending at the entry. The third column (cumulated values) are for the entry value.

X^2	prob.	cumul.	X^2	prob.	cumul.
1.0	0.	0.	26.0	0.0383	0.6818
2.0	0.0000	0.0000	27.0	.0355	0.7172
3.0	0.0000	0.0000	28.0	0.0326	0.7498
4.0	0.0001	0.0001	29.0	0.0296	0.7794
5.0	0.0004	0.0005	30.0	0.0268	0.8062
6.0	0.0011	0.0016	31.0	0.0242	0.8304
7.0	0.0028	0.0044	32.0	0.0216	0.8521
8.0	0.0052	0.0096	33.0	0.0190	0.8711
9.0	0.0088	0.0184	34.0	0.0171	0.8881
10.0	0.0133	0.0318	35.0	0.0150	0.9032
11.0	0.0187	0.0505	36.0	0.0133	0.9165
12.0	0.0239	0.0744	37.0	0.0116	0.9281
13.0	0.0298	0.1042	38.0	0.0100	0.9381
14.0	0.0351	0.1392	39.0	0.0088	0.9470
15.0	0.0401	0.1793	40.0	0.0076	0.9546
16.0	0.0436	0.2230	41.0	0.0065	0.9611
17.0	0.0462	0.2692	42.0	0.0057	0.9668
18.0	0.0482	0.3174	43.0	0.0049	0.9717
19.0	0.0496	0.3669	44.0	0.0043	0.9760
20.0	0.0494	0.4164	45.0	0.0036	0.9796
21.0	0.0492	0.4656	46.0	0.0031	0.9827
22.0	0.0478	0.5134	47.0	0.0027	0.9855
23.0	0.0455	0.5589	48.0	0.0022	0.9876
24.0	0.0435	0.6024	49.0	0.0020	0.9897
25.0	0.0410	0.6435	50.0	0.0016	0.9913

$$Y_i = \sum_{k=-2}^{2} w_k y_{i+k}$$

with, in our particular case, the numerical values: 0.01, 0.208, 0.564, 0.208, 0.01 for w_{-2} to w_2, respectively.

The pseudo-χ^2, let us call it X^2:

$$X^2 = \sum_{i=i_1}^{i_2} (\frac{Y_i - C_i}{\sigma'_i})^2$$

can be readily computed (i_1 and i_2 are respectively the first and the last pixel of the lithium feature), assuming that the y_i are affected by a gaussian noise equal to the noise on each pixel value of the spectrum before convolution (1/650 in fraction of the continuum level). It is a well known result (linear combination of gaussian variables) that the mathematical expectance of X^2 is reduced with respect to the mathematical expectance of the true χ^2 in the ratio:

$$r = \sum_{k=-2}^{2} w_k^2 = 0.4048$$

This gives the value of σ'

$$\sigma' = \sqrt{r} = 0.636\sigma$$

The computation of the complete distribution has been performed by running 1 000 000 realizations, and binning the resulting values of X^2. The results are given in Table A1 for 23 degrees of freedom. This computation shows that the variance is 3.4 times the mathematical expectation, instead of two for a true χ^2 law. So, part of the gain in noise reduction is lost in a shallower distribution, but the gain is anyhow substantial, as already shown, in Sect. 4.1, where the two χ^2 were used competitively. Several simulations, done on test cases, have confirmed the effectiveness of noise filtering, with the use of a modified χ^2 distribution.

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